NEDO-21660
77NED120
Class I
July 1977

EXPERIENCE WITH BWR FUEL THROUGH DECEMBER 1976

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ABSTRACT

This information report provides an updated review of General Electric experience with production and developmental BWR Zircaloy-clad UO_2 fuel rods through December 31, 1976. Previous fuel experience reports (References 1, 2 and 3) have exhaustively discussed experience through September 1974. This report, therefore, concentrates on the most significant experience attained in the intervening period since September 1974 and the introduction of 8x8 fuel.

The "improved" 7x7 and 8x8 fuel performance has been highly successful; of the fuel examined (>200,000 rods), only ~0.05% of the "improved" 7x7 and none of the 8x8 fuel had cladding perforations. This improvement in fuel reliability is due to the elimination of hydriding as an active failure mechanism, fuel design and manufacturing process changes, and general adherence to fuel operating recommendations by reactor owners. At the present time, "improved" 7x7 and 8x8 fuel rods constitute over three-fourths of the GE fuel operating in commercial reactors.

No new failure mechanisms are expected in the current 8x8 fuel design because the current performance requirements placed on the fuel are generally within the experience of statistically demonstrated fuel capability.

General Electric's fuel experience base has increased by over 50% since September 1974. The fuel experience gained, coupled with an expanded developmental data base, supports the basic conclusions of previous experience reports, that the successful irradiations demonstrate that safe and reliable fuel can be designed for modern BWR conditions.

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1. INTRODUCTION

Previous General Electric fuel experience reports (References 1, 2 and 3) have provided a thorough discussion of the operating experience attained with BWR Zircaloy-2 clad UO_2 pellet fuel through September 1974. At that time, ~810,000 General Electric production Zircaloy-2 clad UO_2 pellet fuel rods or segments were in or had completed operation in commercial BWR's. In addition, this production experience was complemented by more than 800 developmental irradiations on rods, segments, and capsules prototypical or very similar to production BWR fuel rods. These developmental irradiations covered powers and exposures significantly beyond those to be experienced by fuel rods in commercial BWR's and thus demonstrated the fuel capability inherent in the BWR fuel rod design. In the intervening period (September 1974 to December 1976), the production fuel experience base has increased by more than 50% with more than 1,250,000 production fuel rods now in or having completed operation in 32 commercial BWR's. Furthermore, many additional developmental irradiations have been completed, or are underway, which are directed toward providing increased understanding and reliability of BWR fuel performance. Although this incremental experience has significantly extended the GE fuel experience base, no new failure mechanisms have been observed. The only mechanisms significantly affecting BWR fuel reliability during this intervening period have been fuel cladding hydriding, which has been eliminated, and pellet cladding interaction (PCI) which has been dramatically reduced. These mechanisms were identified and discussed in previous fuel experience reports (References 2 and 3).

GE launched a comprehensive plan of action in 1972 to substantially reduce or eliminate PCI in GE BWR fuel. The first step in this action plan was to introduce immediate design changes (Reference 2) aimed at reducing localized strains and variability in cladding mechanical properties. This "improved" 7x7 fuel design incorporated a shorter chamfered UO_2 pellet, an increased cladding heat treatment temperature, and hydrogen getters. A second, longer term, design change to an 8x8 fuel matrix was also begun in parallel to reduce fuel thermal duty. In addition, interim plant operating recommendations were made to ameliorate the effects of PCI during the transition to 8x8 fuel with reduced fuel duty. More than two-thirds of the GE fuel currently operating is "improved" 7x7 or 8x8 fuel; these two designs have been extremely reliable to bundle exposures in excess of 20,000 MWd/t.

Reference 3 discussed the characterization of cladding damage by hydriding, steps taken to eliminate hydriding, and early field feedback that hydriding was no longer an active failure mechanism. During the succeeding two years it has been confirmed that hydriding is not an active cladding perforation mechanism for fuel manufactured since mid-1972.

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4. PRODUCTION FUEL EXPERIENCE

4.1 SUMMARY OF PRODUCTION FUEL EXPERIENCE

A large volume of experience with Zircaloy-clad UO_2 pellet fuel has been obtained over the past 17 years. The largest portion of this experience has been obtained in operating commercial power boiling water reactors (BWR) at linear heat generation rates representative of or higher than the current 8x8 or the 8x8R fuel performance requirements. The large volume of production experience, starting with the first load of fuel in Dresden-1 Nuclear Power Station in 1960, has provided feedback on the adequacy of the design for, and the effects of, operation in a commercial power reactor environment. Production fuel experience has also provided feedback on the incidence and effect of flaws and impurities which occur statistically in large volume production processes.

Table 4-1 presents a summary of BWR experience with GE production Zircaloy-clad UO_2 pellet fuel. Overall, 73 production fuel types have been designed, manufactured, and operated in 32 BWR's. When all production fuel types are considered, a total of more than 1,250,000 Zircaloy-2-clad UO_2 fuel rods have been operated in GE designed BWR's. This represents a 55% increase in the GE production fuel experience base since September 1974. Although the available BWR production fuel experience base has increased substantially during this time period, no new failure mechanisms have been observed. Figure 4-1 illustrates GE's experience by exposure interval and bundle design for GE reactors excluding most BWR/1's. Note that some 8x8 and "improved" 7x7 bundles have reached the 15 to 20 GWd/t interval.

Peak linear heat generation rates (LHGR), from approximately 10 kW/ft to approximately 18.5 kW/ft have been experienced with the production fuel. Individual fuel assemblies have achieved average exposures greater than 25,000 MWd/t and have operated approximately 12 years in core residence. In comparison, the current 8x8 and 8x8R fuel designs have the following operating characteristics:

13.4 kW/ft maximum LHGR (Operating Limit)
~40,000 MWd/t maximum local exposure
~30,000 MWd/t maximum assembly exposure
4 to 6 years in-core residence time

Fuel rod diameters in the range of 0.425 inch to 0.593 inch o.d. with cladding wall thickness from 30 to 40 mils and pellet-to-cladding gaps from 3 to 12 mils have been used in production fuel. Active fuel column lengths have varied from 59.8 to 146.0 inches with fission gas plenum volume per unit of fuel volume from 0.013 to 0.11. In comparison, Table 4-2 describes the pertinent characteristics of the three categories of fuel types currently operating in BWR's 2 through 4.

Figure 4-2 illustrates the chronological introduction of the "improved" 7x7 and 8x8 fuel designs into BWR's 2 through 4. Note that even with the introduction of the "improved" 7x7 fuel design in 1973 and the 8x8 design in 1974, it will be several years before the old 7x7 fuel design will be completely phased out of reactor usage because of the expected 4- to 5-year lifetime of BWR nuclear fuel. Also note, however, that more than three-fourths of the GE fuel currently operating is either 8x8 or "improved" 7x7 fuel.

4.2 FUEL ROD PERFORATION EXPERIENCE

The early GE BWR fuel experience has been extensively described in previous experience reports (References 1, 2 and 3). In general the Zircaloy-2 clad fuel performance in the very early plants was good, but several problems, summarized in Table 4-3, were identified and corrected. These earlier problems are not significantly affecting fuel performance at the present time.

Pellet cladding interaction (PCI) and, to a much lesser extent, crud-induced failures and hydriding are the only clad perforation mechanisms which have affected fuel performance in the last two years. The "improved" 7x7 fuel has been highly successful with only ~0.05% of the ~100,000 fuel rods examined having cladding perforations. Of these 0.01% are attributed to crud induced failures and the remainder to PCI. The majority of the PCI perforations (0.03%) resulted from a single instance of exceeding the Preconditioning Interim Operating Management Recommendation (PCIOMR).

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Table 4-1
SUMMARY OF EXPERIENCE IN PRODUCTION ZIRCALOY-CLAD UO_2 FUEL
(DECEMBER 31, 1976)

Class of Reactor	Reactor	Fuel Type	No. of Bundles	Exposure Peak Pellet (MWd/t)	Exposure[1] Average Assembly (MWd/t)	Time in Core (Years)	Design Peak LHGR kW/ft	Fuel Rod[2] Diameter (in.)	Cladding[3] Thickness (mils)	Pellet-to-Cladding Gap (Nominal mils)	Active Fuel Length (in.)	Number Segments (S) or Rods: Total	Number Segments (S) or Rods: Still in Core
1	Dresden 1	1	536	21,000	8,200	9.0	~14.4	0.567	33	7.0	106.5	77,184(S)	0
		111B	192	27,000[4]	~18,500[4]	9.5[5]	15.4	0.555	35	7.5	109	6,912	1,080[4]
		111F	104	31,000[4]	~23,000[4]	8.5[5]	15.5	0.5625	35	10	108.25	3,744	468[4]
		V	106	28,000[4]	~18,000[4]	6.5[5]	15.5	0.5625	35	10	108.25	3,816	2,556[4]
—	RWE-KAHL		100	~19,000	~10,000	—	—	0.569	33	5	59.75	7,200(S)	0
1	Garigliano	A	208	26,600	14,300	11.9	10.3	0.534	30	5	105.7	16,848	0
		SA	66	29,500	19,600	8.2	14.6	0.593	37	11	107	4,224	3,200
		SB	72	24,900	15,500	6.3	14.6	0.593	37	11	107	4,608	3,200
		SC	62	17,800	10,600	4.0	14.6	0.593	37	11	107	3,968	3,968
		SD	46	7,300	4,300	1.2	13.4	0.593	37	11	107	2,944	2,944
—	JPDR		78	—	~3,400	—	—	0.567	30	5	56.75	5,472(S)	0
1	Consumers (BRP)	B	30	35,400	23,400	5.0	15.0	0.449	34	8	70.0	3,630	0
		E	41	16,000	9,400	3.2	17.7	0.5625	40	11	70.0	3,321	0
		EG	33	23,700	17,300	6.0	17.7	0.5625	40	11	70.0	2,673	0
		F	85	20,300	14,800	4.3	17.7	0.5625	40	11.5	70.0	6,885	2,916
1	Humboldt	11	169	23,000	14,600	8.0	12.1	0.486	33	10	79.0	6,084	0
		111	176	24,000	12,800	4.4	16.8	0.563	32	11	79.0	6,336	4,212
1	KRB	A	371	26,500	15,800	7.7	15.8	0.5625	35	10	130	13,356	504
		KD	40	21,500	12,500	4.0	15.8	0.563	32	11	130	648	288
1	Tarapur 1	T	301	29,600	17,200	7.9	15.8	0.5625	35	10.5	144	10,836	2,628
	Reload	TA	67	23,600	13,600	4.7	15.8	0.563	32	10.5	142.25	2,412	1,908
		TB	74	19,400	11,000	2.4	15.8	0.563	32	10.5	142.25	2,664	2,160
1	Tarapur 2	T	308	29,000	17,500	7.8	15.8	0.5625	35	10.5	144	11,088	5,184
	Reload	TA	37	17,000	11,200	4.0	15.8	0.563	32	10.5	142.25	1,332	540
		TB	14	13,900	8,300	2.4	15.8	0.563	32	10.5	142.25	504	432
2	Oyster Creek	JC	560	30,900[6]	18,700[6]	7.6[6]	17.2	0.570	35.5	11	144	27,440	9,016[6]
	Reload	JCA	156	20,400[6]	12,600[6]	5.1[6]	17.2	0.563	32	12	144	7,644	7,448[6]
2	Nine Mile Point 1	NM	532	27,700	18,500	7.3	17.5	0.570	35.5	11	144	26,068	1,862
	Reload	NMA	56	25,100	16,200	5.2	17.5	0.563	32	12	144	2,744	2,744
		GEA	40	28,400	19,700	4.5	17.5	0.563	32	12	144	1,960	1,666
		NMC	108	25,100	16,900	3.5	17.5	0.563	37	12	144	5,292	5,292
		NMD	96	18,700	12,300	2.5	13.4	0.493	34	9	144	6,048	6,048
		LJ	200	8,800	5,800	1.0	13.4	0.493	34	9	144	12,600	12,600
2	Tsuruga	JA	314	26,600	18,700	7.3	17.5	0.570	35.5	12	144	15,386	539
	Reload	JAA	48	30,600	21,500	6.1	17.5	0.563	32	12	144	2,352	882
		JAB	85	23,200	15,600	4.1	17.5	0.563	32	12	144	4,165	1,911
		JAC	76	20,500	11,600	3.5	17.5	0.563	37	12	144	3,724	3,381
		JAD	53	13,300	7,700	2.4	17.5	0.563	37	12	144	2,597	2,597
		JAE	82	9,600	5,400	1.3	17.5	0.563	37	12	144	4,018	4,018
		JAF	36	4,100	2,600	0.3	13.4	0.493	34	9	144	2,268	2,268
3	Dresden 2	DN	724	6,600	3,300	2.3	17.5	0.563	32	12	144	35,476	0
	Reload	DD	29	2,100	1,300	0.5	17.5	0.563	32	12	144	1,044	0
		CY	215	23,300	15,300	5.7	17.5	0.563	32	12	144	10,535	6,958
		DN	509	23,800	16,300	4.7	17.5	0.563	32	12	144	24,941	13,230

See footnotes at end of table

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Table 4-1
SUMMARY OF EXPERIENCE IN PRODUCTION ZIRCALOY-CLAD UO_2 FUEL
(DECEMBER 31, 1976) (Continued)

Class of Reactor	Reactor	Fuel Type	No. of Bundles	Exposure Peak Pellet (MWd/t)	Exposure[1] Average Assembly (MWd/t)	Time in Core (Years)	Design Peak LHGR kW/ft	Fuel Rod[3] Diameter (in.)	Cladding[3] Thickness (mils)	Pellet-to-Cladding Gap (Nominal mils)	Active Fuel Length (in.)	Number Segments (S) or Rods: Total	Number Segments (S) or Rods: Still in Core
		GEB	32	9,800	6,900	1.6	17.5	0.563	37	12	144	1,568	1,372
		LJO	276	11,900	5,233	[illegible]	13.4	0.493	34	9	144	17,388	17,388
		GBH	8	5,600	4,000	0.8	13.4	0.493	34	9	144	504	504
3	Dresden 3	DD	724	23,500	15,600	5.9	17.5	0.563	32	12	144	35,476	16,660
	Reload	GEB	52	15,900	11,100	3.6	17.5	0.563	37	12	144	2,548	2,548
		GEH	44	13,800	9,800	2.5	13.4	0.493	34	9	144	2,772	2,772
		LJO	132	9,300	6,000	1.3	13.4	0.493	34	9	144	8,316	8,316
		GBH	8	6,200	4,500	1.3	13.4	0.493	34	9	144	504	504
		LJ4	148	1,100	700	0.3	13.4	0.493	34	9	144	9,324	9,324
3	Millstone 1	MS	560	25,700	14,000	6.2	17.5	0.570	35.5	12	144	28,420	4,557
	Reload	GEA	82	22,900	14,900	3.8	17.5	0.563	32	12	144	4,018	3,283
		GEB	[illegible]	23,300	15,300	3.8	17.5	0.563	37	12	144	1,470	1,421
		MSB	125	15,900	10,000	2.1	17.5	0.563	37	12	144	6,125	6,076
		LJ	143/124	9,000	3,300	1.1/0.1	13.4	0.493	34	9	144	16,821	16,821
3	Fukushima 1	TX	404	22,300	13,800	6.4	17.5	0.570	35.5	12	144	19,796	9,800
	Reload	TXA	60	13,100	7,200	5.1	17.5	0.563	32	12	144	2,940	2,401
		TXB	111	11,900	5,700	1.0	17.5	0.563	37	12	144	5,439	5,439
		TXC	40	3,500	1,900	1.0	17.5	0.563	37	12	144	1,960	1,960
3	Monticello	MT	484	25,100	14,200	5.0	17.5	0.563	32	12	144	23,716	0
	Reload	GEB	20	24,100	17,300	3.6	17.5	0.563	37	12	144	980	980
		MTB	116	19,400	10,800	2.6	13.4	0.493	34	9	144	7,308	7,308
		GBH	80	15,600	9,500	1.8	13.4	0.493	34	9	144	5,040	5,040
		LJ	268	9,800	6,500	1.1	13.4	0.493	34	9	144	16,884	16,884
3	Nuclenor	NU	404	26,100	17,100	6.2	17.5	0.570	35.5	12	144	19,796	2,842
	Reload	GEA	28	26,700	17,700	4.3	17.5	0.563	32	12	144	1,372	1,176
		NUB	68	24,800	16,200	3.6	17.5	0.563	37	12	144	3,332	3,234
		NUC	96	21,200	12,500	2.6	13.4	0.493	34	9	144	6,048	6,048
		LJ	60/96	14,400	5,730	0.7/1.6	13.4	0.493	34	9	144	9,828	9,828
3	Quad Cities 1	CX	724	24,100	15,100	5.2	17.5	0.563	32	12	144	35,476	24,696
	Reload	GEB	28	17,100	10,900	2.4	17.5	0.563	37	12	144	1,372	1,372
		GEH	31	17,000	11,500	2.4	13.4	0.493	34	9	144	2,268	2,268
		LJ	156	6,500	4,000	0.8	13.4	0.493	34	9	144	9,828	9,828
3	Quad Cities 2	CY	724	23,800	14,900	4.7	17.5	0.563	32	12	144	35,476	18,816
		CX	31	19,700	13,800	1.2	17.5	0.563	32	12	144	1,519	1,372
		LJ	298	11,900	4,300	1.7/0.9	13.4	0.493	34	9	144	18,774	18,774
		GBH	14	1,400	1,000	0.1	13.4	0.493	34	9	144	882	882
3	Pilgrim 1	BE	580	19,700	12,381	4.0	17.5	0.563	32	12	144	28,420	20,972
		BEA	20/40	11,700	4,000	2.4/0.6	13.4	0.493	34	9	144	1,260	1,260
		LJ	92	4,900	3,000	0.6	13.4	0.493	34	9	144	5,796	5,796
4	KKM	AM	232	29,100	15,000	5.3	18.5	0.563	32	12	144	11,368	0
	Reload	GED	12	18,400	12,900	2.9	18.5	0.563	37	12	144	588	588
		AMA	108	21,900	13,500	2.2	13.4	0.493	34	9	144	6,804	6,804
		LJ	120	12,900	4,600	1.3	13.4	0.493	34	9	144	7,560	7,560

See footnotes at end of table

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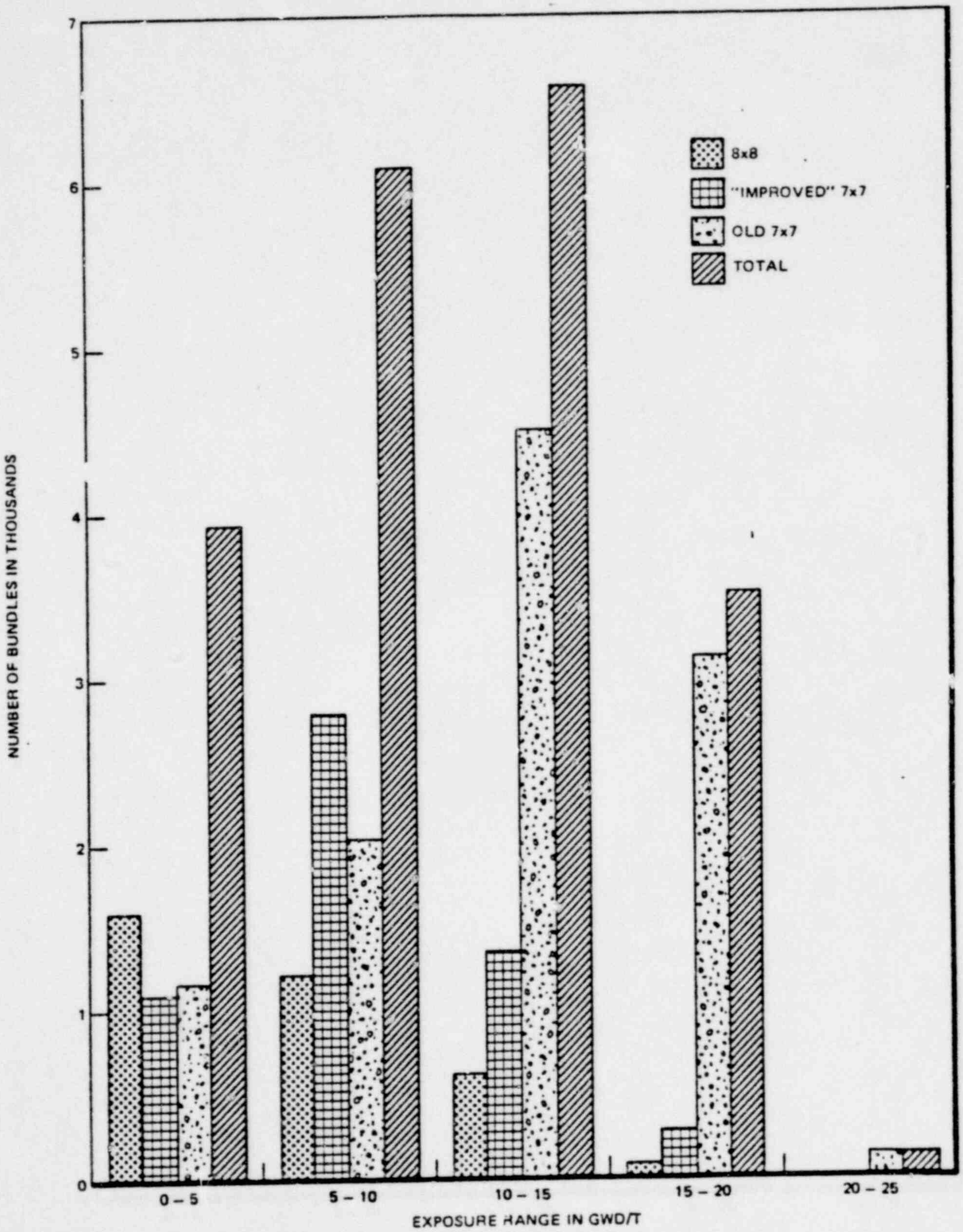
Table 4-1
SUMMARY OF EXPERIENCE IN PRODUCTION ZIRCALOY-CLAD UO_2 FUEL (DECEMBER 31, 1976) (Continued)

Class of Reactor	Reactor	Fuel Type	No. of Bundles	Exposure Peak Pellet (MWd/t)	Exposure[1] Average Assembly (MWd/t)	Time in Core (Years)	Design Peak LHGR kW/ft	Fuel Rod[3] Diameter (in.)	Cladding[3] Thickness (mils)	Pellet-to-Cladding Gap (Nominal mils)	Active Fuel Length (in.)	Number Segments (S) or Rods: Total	Number Segments (S) or Rods: Still in Core
4	Vermont Yankee	VT	376	13,000	7,600	2.6	18.5	0.563	32	12	144	18,424	0
	Reload	GED	40	15,400	9,600	3.1	18.5	0.563	37	12	144	1,960	1,960
		LJ	328/134	18,300	7,900	2.0/0.3	13.4	0.493	34	9	144	28,602	20,538
		LJLTA	2	2,900	2,200	0.3	13.4	0.483	32	9	150	126	126
4	Browns Ferry 1	TY	168/596[2]	11,500	6,700	3.5[2]	18.5	0.563	32/37	12	144	37,436	37,436
4	Browns Ferry 2	TZ	168/596[2]	5,900	3,400	2.4[3]	18.5	0.563	32/37	12	144	37,436	37,436
4	Browns Ferry 3	BF	764			0.3	13.4	0.493	34	9	146	48,132	48,132
4	Peach Bottom 2	PH	168/596[2]	22,100	13,700	3.3	18.5	0.563	32/37	12	144	37,436	28,224
		LTL	4	5,400	3,953	0.5	13.4	0.493	34	9	150	252	252
		LJ3	184	5,200	3,400	0.5	13.4	0.493	34	9	144	11,592	11,592
4	Peach Bottom 3	PB	764	18,000	10,700	2.4	18.5	0.563	37	12	146	37,436	37,436
4	Fukushima 2	FU	554	16,300	9,700	3.8	18.5	0.563	32	12	144	27,126	26,411
		FUA	9	3,500	2,400	1.8	18.5	0.563	37	12	144	441	441
4	Cooper	CZ	128/420[2]	17,800	10,400	2.9	18.5	0.563	32/37	12	144/146	26,852	20,972
		LJ	120	—	—	0.1	13.4	0.493	34	9	144/146	7,560	7,560
4	Duane Arnold	AR	368	18,400	11,100	2.8	18.5	0.563	37	12	144	18,032	13,720
	Reload	GED	4	7,600	5,500	0.8	18.5	0.563	37	12	144	196	196
		LJ	84	6,600	4,800	0.8	13.4	0.493	34	9	144	5,292	5,292
4	Hatch	HX	560	12,900	8,100	2.3	18.5	0.563	37	12	144	27,440	27,440
4	FitzPatrick	EA	132/428[2]	12,600	7,200	2.1	18.5	0.563	32/37	12	144	27,440	27,440
4	Brunswick 2	BR	560	7,600	4,500	1.6	18.5	0.563	37	12	144	27,440	27,440
	Reload	GED	4	1,800	1,000	0.6	18.5	0.563	37	12	144	196	196

[1] Assembly average exposure for those assemblies remaining in the core or assembly average discharge exposure when no assemblies remain in the core.
[2] Approximately 1/4 core was the old 7x7 fuel design and the remaining ~3/4 core the "improved" 7x7 fuel design.
[3] "Improved" 7x7 fuel rod has a 0.563 inch diameter and a 37-mil wall thickness. The 8x8 rod has a 0.493 inch diameter and a 34-mil wall thickness.
[4] Information as of March 29, 1976
[5] Information as of September 30, 1974



*BWR 2, 3 AND 4'S PLUS GARIGLIANO AND TARAPUR 1 AND 2

Figure 4-1. Histogram of Total Number of GE Bundles versus Discharge or Current Exposure by Fuel Type*

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BWR 2, 3 and 4's Plus Garigliano and Tarapur 1 and 2

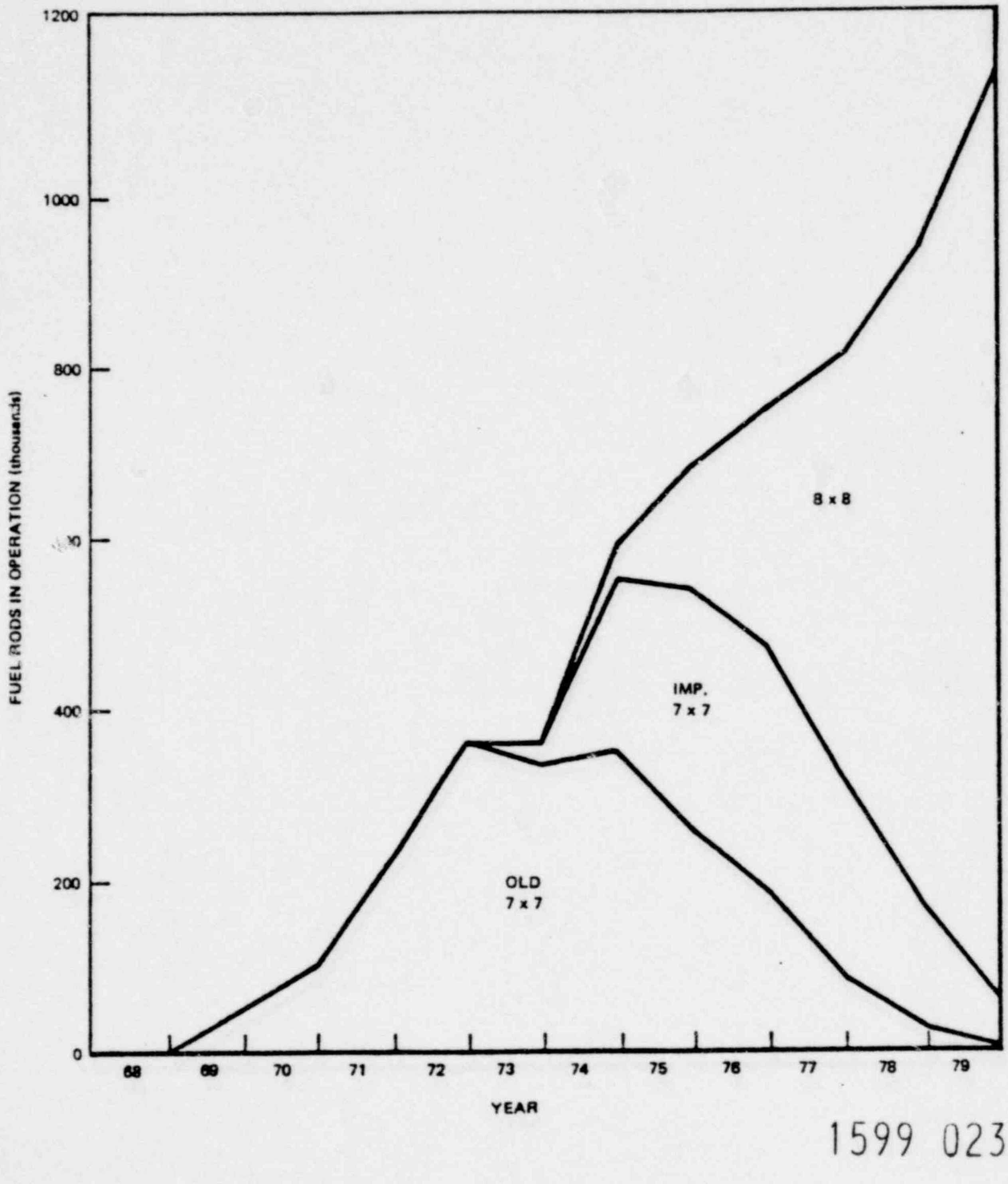

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Figure 4-2. Number of Fuel Rods Operating in BWR2/4 Reactors